Taxonomy of Visualization Techniques and Systems – Concerns between Users and Developers are Different

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ABSTRACT

Geo-visualization brings whole new meanings and techniques for spatial analysis. Many visualizations techniques are developed and used for geo-domain. The taxonomy of visualization can help developers to grasp the key techniques of visualization. It also helps domain users to understand how some one visualization technique works and to choose the fit technique to use for analysis. Some researches on taxonomy adopt one or more factors, such as data type, display style, interactivity, etc. But all these frameworks treat the developers and the users as the same. But there are different concerns between algorithm developers and technique users. So this paper gives two classifications. The classification for visualization technique developers uses two factors, i.e. data type and analytic task. And the classification for user applies representation style and interactivity degree as factors. This framework shows our standpoint that visualization merges representation function and interaction function and its real role is analysis rather than display. Former classification or surveys on visualization often mix up techniques and systems. But they are in different level. We present taxonomy for systems to clarify this confusion. Based on this new taxonomy framework, this paper discusses the present status on research of geo-visualization techniques. It is shown that the research is stepping from visualization representation to visualization analysis, which is closer to the full meaning of visualization.

KEY WORDS: Geo-visualization, Visualization technique, Visualization system, Taxonomy

1. Introduction

After visualization was proposed in 1986 (McCormick et al., 1987), Geo-specialists responded fast and broadly (DiBiase, 1990; Taylor, 1994; MacEachren, 1994; MacEachren and Kraak, 1997). MacEachren et al. (1992) defines the Geo-visualization as "*... the use of concrete visual representations…to make spatial contexts and problems visible, so as to engage the most powerful human information-processing abilities, those associated with vision.*" The key to understand visualization is to think it as a process associated with human visual thinking, handling spatial data by computer, and human-computer interaction. Geo-visualization brings whole new meanings and techniques for spatial analysis.

During research for more than twenty years, many visualization techniques have been developed with different ways for many fields and goals. They are all helpful for geo-visualization and geographical research, more or less. A taxonomy framework is needed for understanding their way of think, function, application scope, usage, etc.

Simon (1969) said that "*an early step towards understanding any set of phenomena is ... to develop a taxonomy*". The importance of taxonomy for visualization techniques are two folds: 1) to make their thinking way and application goal clear, so to help user to choose fitful visualization technique for question of applied field; and 2) discover the shortage of present visualization research, so to promote researchers to develop new visualization techniques (Buja et al., 1996).

But the research on taxonomy for visualization is inadequate. This paper reviews the former main frameworks in Section 2. Then our taxonomy is provided in Section 3. Section 4 presents taxonomy of visualization systems to clarifying the confusion that some former classification mixed up techniques and systems. Finally, Section 5 summarizes whole paper and discusses the research trend of geo-visualization techniques based on our classification.

2. Review of taxonomy of visualization

There are many taxonomic reviews about visualization. But many of them are on some one aspect, not full-scale. For example, Herman (2000) reviewed visualization of structural data by graph layout, navigation and interaction. Leung and Apperley (1994) gave a detailed survey on distortion techniques of visualization.

The integrated taxonomy of visualization was mentioned initially in few books. With the continual development of representation and interaction techniques of visualization, some research focus on more systematical, global taxonomy frameworks since 1995. They employed single factor or multiple factors.

2.1 Framework with single factor for visualization techniques

Totally, there are five factors for current classification of visualization techniques: 1) data type; 2) display mode; 3) interaction style; 4) analytic task; 5) based model.

2.1.1 Framework with factor of data type

The classification with factor of data type is concise for visualization users. It was earliest emerged and applied frequently. Factors of data type in several frameworks are almost identical. Earlier, Shneiderman (1996) adopted seven data types, i.e., 1D, 2D, 3D, time, multi-dimension, tree, network. Shneiderman separated time data type from 1D data type because he thought 1D data type mainly covers text data. He further analyzed seven analytic tasks that may be used for every data type, i.e., overview, zoom, filter, details-on-demand, relate, history, extract. These seven tasks mix interaction and analytic task up. It is vague. For example, zooming is one task of interaction and is improper to think it as a goal task of visualization.

The students in Sheneiderman's class, Information Visualization, set up an online library for visualization by classification based on data type (OLIVE, 1997). They classified out eight data types by adding Workspace type into Shneiderman's seven data types. The visualization techniques of Workspace type organize views for more display space by interaction or use new information interaction to change work environment. But it is unfit to think it as a data type in taxonomy framework.

Card et al. (1999) classified out seven data types: physical data, 1D, 2D, 3D, multi-dimension, tree, and network. These are from the district of scientific visualization and information visualization.

There has a problem in taxonomy based on data type. During the visualization process, either developers of visualization algorithm or users of visualization system explain the data (Tory and Möller, 2002). So the data type may be changed. And more important is all these frameworks just focus on visualization representation and miss thinking about the interaction process. They are not complete.

2.1.2 Framework with factor of display mode

The classification based on display mode is intuitive. Keim and Kriegel (1996) classified the visualization techniques as five classes according to their display mode.

1) Pixel-oriented techniques. They deal the arrangement of pixels for purpose of application, such as query-independent pixel-oriented techniques with display of space-filling mode, or query-dependent pixel-oriented techniques (e.g. spiral pixel-arrangement techniques).

2) Geometric projection techniques. They just fit for the visualization of multi-dimensional small-size dataset. Examples are scatter plot, parallel coordinates, etc.

3) Icon-based techniques. Examples are shape coding, color icons, Chernoff faces, stick figure, star glyphs (Fienberg, 1979), and so on.

4) Hierarchical techniques. They subdivide the k-dimensional space and present the subspaces in a hierarchical fashion, e.g. n-Vision, dimensional stacking, and treemap.

5) Graph-based techniques. They use specific layout algorithms, query languages, and abstraction techniques to effectively present a large graph. Examples are Hy+, Margritte, SeeNet.

2.1.3 Framework with factor of interaction style

Both former two classes of taxonomy neglect interaction and think visualization as visualization representation. We think the complete meaning of visualization should contain two folds with same importance, i.e. representation and interaction. Some researchers show same point by emphasizing the concept of interactive visualization.

Buja et al (1996) classified visualization as two basic parts: display of static view (correspond to visualization representation), interactive handle. They proposed taxonomy based on data analytic tasks: finding Gestalt, posing query, and making comparisons. These tasks are supported with three classes of interactive view manipulations (i.e. focusing, linking, and arranging views). The visualization representation is classified as three styles: scatter plot, functional transformation, and glyphs. Although this taxonomy just focused on visualization of high-dimensional data and their classification for interactive tasks and representation styles is comparatively coarse, but they emphasized the interaction.

Chuah and Roth (1996) summarized a set of basic visualization interaction (BVI, which is defined with all three folds: input, output, and operation). They classified

visualization by their tasks (fig. 1). This framework is implementation-oriented classification by means of decomposing the user-interface of visualization system as basic interactive components. This way of thinking from interaction helps developer to compare and re-use the BVIs. The complex interaction can be formed by combination of BVIs.
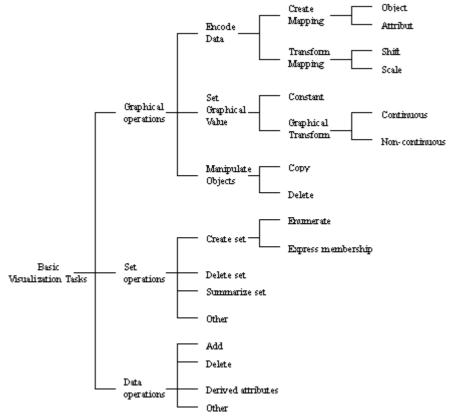

Figure 1. Chauh and Roth's Basic Visualization Interaction classification hierarchy
(from Chauh and Roth, 1996)

2.1.4 Framework with factor of analytic tasks
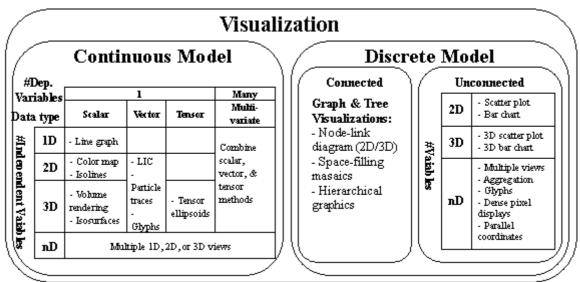Table 1. Zhou and Feiner's visual implications and related elemental tasks (from Zhou and Feiner, 1998)

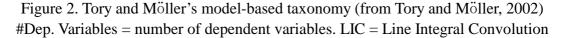| Implication	Type	Subtype	Elemental tasks
Organization	Visual grouping	Proximity	associate, cluster, locate
		Similarity	categorize, cluster, distinguish
		Continuity	associate, locate, reveal
		Closure	cluster, locate, outline
	Visual attention		cluster, distinguish, emphasize, locate
	Visual sequence		emphasize, identify, rank
	Visual composition		associate, correlate, identify, reveal
Signaling	Structuring		tabulate, plot, structure, trace, map
	Encoding		label, symbolize, portray, quantify
Transformation	Modification		emphasize, generalize, reveal
	Transition		switch

4

Wehrend and Lewis (1990) proposed taxonomy based on analytic tasks which are independent of application fields. They classified the users' analytic tasks as ten classes: location, identity, distinguish, categorize, cluster, distribution, rank, compare within entities, associate, and correlate.

Zhou and Feiner (1998) extended the Wehrend and Lewis' thought. On the one hand, they abstracted analytic tasks of visualization as visual implications. On the other hand, they detailed the elemental tasks of visualization (Table 1).

2.1.5 Framework with factor of based model

Tory and Möller (2002) set up a taxonomy based on used data-model. The data models used in visualization were classified as discrete or continuous. The continuous data model mainly deals scientific visualization. Below it, more detailed classification is made by number of independent variables (i.e. dimensions), number of dependent variables, and data types. The discrete data model mainly deals information visualization. Below it, subclasses are made according to connected or unconnected (fig. 2). This framework needs users to distinguish dependent and independent variables. But when user faces a high-dimensional database, this work is not always easy. So, this framework maybe more fit for the need of theoretical research of visualization.

Figure 2. Tory and Möller's model-based taxonomy (from Tory and Möller, 2002)
#Dep. Variables = number of dependent variables. LIC = Line Integral Convolution

Chi (2000) thought that classification based on data type is not helpful to understand how to use and how to implement visualization technique. So he adopted the data state reference model associated with the operator model proposed by Chi and Riedl (1998). In their taxonomy (Chi and Riedl, 1998; Chi, 2000), every visualization technique was discomposed as four Data Stages, three types of Data Transformation, and four types of Within Stage operators (fig. 3). Four Data Stages, i.e. value, analytical abstraction, visualization abstraction, and view, change in succession by corresponsive data transformation, i.e. data transformation, visualization transformation, and visual mapping transformation. Within every data stage, the Within Stage operators do not

change the structure of data processed. In operator model, the closer the operator is to view, the wider the application scope of operators is and the higher its interactivity is.
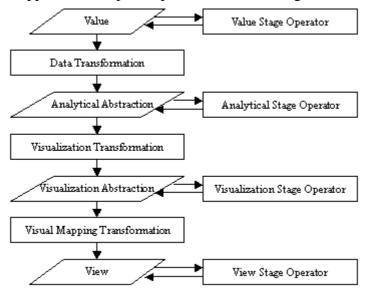

Figure 3. Chi's Data Stage model of visualization (after Chi, 2000)

The data state reference model provides a fine data-flow graph of visualization techniques, specially for visualization representation. This analysis by operator mode can reveal the dependency among visualization modules and the difference and similarity among visualization techniques. For example with visualization for hierarchical information, both Disk Tree and Cone Tree can be used and there are some share steps. This is helpful for developers to integrate many techniques into a visualization system. The difference among similar techniques for same data type is often at the operators of visual mapping transformation, which is the process of transforming visualized information into visual format and forming graphic view. Many current researches on visualization techniques are on the algorithm design in this stage of visualization representation. And the researches on directly handling interaction mainly belong to view stage operator.

But in practice, Chi (2000)'s classification is according to application fields, which included scientific visualization, geographical-based info visualization, 2D, multi-dimensional plot, information landscapes and spaces, …, totally ten classes. And the data state model is used to describe the operation process of some one technique. The ambiguous is to mix up applied fields, data type, and display modes. And the systems and techniques are put together and discussed under the same framework.

The description and comparison for visualization techniques can help researchers to wholly understand their process and function. But it is not taxonomy in rigid meaning. These cases include not only Chi and Riedl (1998) and Chi (2000), but also Card and Makinlay (1997)'s description framework with semiology.

Card and Makinlay (1997) set up a semiology for description of visualization. By this framework, every variable of some one technique has three folds to be described in visualization process: 1) change and change type of data type; 2) the map between data dimensions and visual properties; 3) the process of related control. This description

framework is not taxonomy, but it helps us to understand visualization techniques. Card and Makinlay (1997) used this framework to discuss techniques of some main fields of visualization, such as scientific, GIS, tree, etc. They conclude that current visualization techniques mainly focus on the stage of representation for target dataset and control process provided by some techniques are mostly about scope selection and data reduction (or, zoom and filter in interaction).

2.2 Framework with multiple factors for visualization techniques

In researches of taxonomy, the frameworks with single factor are often dissatisfactory. At least, two basic parts, i.e. representation and interaction, can be hardly unified under one factor. One example is de Oliveira (2003)'s classification table for visualization. She collected many visualization techniques and classified them with representation and interaction respectively by Card and Mackinlay (1999)'s and Keim and Kregel (1996)'s framework. This way results that some techniques with representation and interaction together are hard to be classified. So, frameworks with multiple factors are emerged.

Keim (2001, 2002) re-classified five classes of visualization by display mode (Keim called as "Visualization techniques"): standard 2D/3D display, geometrically-transformed display, iconic display, dense pixel display, and stacked display (same as Keim and Kriegel (1996)'s type of hierarchical visualization). He dealt display mode as a dimension. After combined with two other classifying dimensions -- data type, interaction and distortion, an orthogonal taxonomy was set up (fig. 4). Orthogonality means that any of the display modes may be used in conjunction with any of the interaction styles as well as any of the distortion styles for any data type (Keim, 2002). The data type includes 1D, 2D, multi-dimensional, text/web, hierarchies/graphs, and algorithm/software. The interaction and distortion is classified as standard, projection, filtering, zoom, distortion, link and brush.
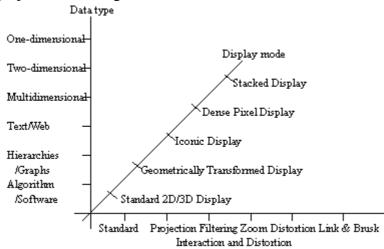

Figure 4. Keim's 3-factor orthogonal framework for visualization (after Keim, 2002)

Keim's 3-factor orthogonal framework is complete because every visualization technique can find its position. But the orthogonality maybe mislead users to think that any of display modes combined any of interaction and distortion can be used for any

data type because there is corresponding sub-class in framework. But in fact, different type of display modes fits for corresponding data type, and different type of interaction and distortion has corresponding task. For 1D data as example, dimension stacked display and link-brush interaction are unfit. But this thought of multi-factor framework is proper for taxonomy of visualization, which associate simultaneously and tightly with several factors. And heretofore, this taxonomy is the most complete and clearest one.

Tweedie (1997) analyzed many techniques and systems of visualization from representation of data type and interactivity, but she did not form a systematic taxonomy. Tweedie classified data type according to Bertin (1981)'s classification of data value-structure and she also considered the transformed type between value and structure. The classification of interaction is artificially segmented the scope from wholly manual and automatic interaction as five classes: manual, mechanized, instructable, steerable, and automated.

Pfitzner et al. (2003) presents a taxonomy that characterizes it in terms of five factors, i.e. data, task, skill, context, and interaction. Data factor includes data types of three types (object, attribute, and meta-information) and data relationships of five types (linear, circular, ordered tree, un-ordered graph, and lattice) adapted from Bertin (1981). The task factor adopted Shneiderman (1998)'s seven interaction tasks. The interaction factor agrees with Tweedie (1997)'s classification for interactivity. Users' skill level maybe novice, or expert. The contextual dimension includes user life experience, history, user intent, user need, and device.

Pfitzner et al. (2003)'s framework considers all factors of human, computer, and environment related with visualization. And the relationship and effect among factors are analyzed. It can help understand concept and process of visualization. But the framework is too complicated to use for classification of practical visualization techniques.

3. Our taxonomy of visualization techniques

Just as Chi and Riedl (1998) note, the concerns between users and developers of visualization techniques are different. Therefore we prompt different framework for each type human. The users pay close attention to which technique can meet our application dataset and fulfill the analytic task. So we propose taxonomic framework of data type – analytic task. And the developers pay more attention to which data structure to be used, how to arrange the views, what operations to be provided for users, and so on. So we adopt framework of representation mode – interaction level. Each framework forms a two-dimensional table for classification of visualization techniques.

Table 2. User-oriented framework for visualization techniques

Analytic task / Data type	overview-query	comparison	cluster-classification	distribution pattern	dependency-correlation analysis
1D	Animation; LifeLine; line grapht; colormap; curve density plot	Pie plot; line graph	Colormap; curve density plot	value bar; curve density plot; histogram	
2D	Geographic map; scatter plot; colormap	Geographic map; scatter plot	colormap	Isogram plot	AViz
3D	Visible Human; volumn rendering; scatter plot	scatter plot	colormap		
Multi-dimensional	Table Lens; n-Vision; Scatterplot Matrix; GrandTour; star glyphs	Andrews Curve; star glyphs	Parallel Coordinates; InfoCrystal; WinViz; HD-Eye	Circle Segments; InfoCrystal; GrandTour; project pursuit; FastMap	Scatterplot Matrix; Dimension Stacking
hierarchical	Hyperbolic view; Magic Eye View; Cone Tree; Disk Tree			Treemap; Information Cube	
graph	DA-Tu; Fisheye view; WebBook & WebForage			NetMap	WebView
Text/hypertext	Perspective Wall; Document Lens	TileBars	InfoCrystal	TileBars; InfoCrystal	NetMap

Table 3. Developer-oriented framework for visualization techniques

Interaction level / Representation mode	Manual handle	Mechanized interaction	Steerable analysis
pixel-oriented	Circle Segments; value bar; color map; curve density plot	Table Lens; Visible Human	
geometric projection	Geographic map; point plot; Scatterplot matrix; Landscape; project pursuit	Parallel Coordinates; WinViz; Starfield	
function transformation	InfoCrystal; Andrews Curve; Isogram plot; FastMap; multidimensional scaling	GrandTour	
icon-based	Boxplot; Pie plot; LifeLine; line graph; star glyphs; histogram	Linking & Brush; stick figure; Chernoff faces; TileBars	HD-eye
hierarchy-based	Treemap; Cone Tree; Dimensional Stacking; Information Cube; Disk Tree	n-Vision; Hyperbolic view; Magic Eye View	AViz
graph-based	NetMap; animation; WebView	Fisheye view; Perspective Wall; WebBook & WebForage	DA-TU

 Note: If there is any name identical with some one visualization system in Table 2 or 3, it means the name of visualization technique in that system in which there is sole (or core) visualization technique and no standalone name.

3.1 Framework of data type – analytic task for users

In user-oriented framework, the factor of data type includes 1D (include time series data), 2D (e.g. data for map and GIS), 3D (mainly volume data), multi-dimensional (e.g. multi-dimensional table in relational database), hierarchical (such as tree), graph (e.g. data with network and grid structure), and text/hypertext (also include program code and Web contents). The factor of analytic task includes overview-query, comparison, cluster-classification (outlier analysis is also belong this type because outlier and cluster are a couple of cross problems), distribution pattern, dependency-correlation analysis.

Table 2 shows the classification for some main visualization techniques with this framework. Some visualization techniques, e.g. colormap, maybe fit for several data type or analytic tasks and can be filled in several grids in Table 2. We find that techniques for deeper analysis are much fewer than those for overview-query and comparison.

3.2 Framework of representation mode – interaction level for developers

In developer-oriented framework, the factor of representation mode includes pixel-oriented, geometric projection, function transformation, icon-based, hierarchy-based, and graph-based. The factor of interaction level includes manual (such as zoom and select by click-drag with mouse, selection by typing SQL statement, even nothing interactivity at all after display), mechanized (e.g. slider, linking brush), and steerable (which have most automatic interactivity, e.g. analysis with given interaction program or some one visual data mining algorithm).

Table 3 shows the classification application with this framework. Obviously, techniques with interactivity of steerable analysis are few.

4. Our taxonomy of visualization systems

Visualization system is integrated implementation of visualization techniques for application. A system always contains many techniques. And one technique can be implemented in many systems. A good example is map display being the basic function of all of GISs. Not a few of current taxonomies classify techniques and systems within same framework (e.g. OLIVE, 1997; Chi, 2000). They confuse systems on application level with techniques on technology level. We try to clarify this confusion by provide a taxonomy for systems in this section.

There is classification for visualization systems that divides systems as some generations. Gobel (1994) classified visualization systems as three generations. First is graph library, developed from mid of 70s in 20th century, which include OEXlib, OpenGL, GL, GKS3D, etc. They mostly have function for 3D graphic programming. The second generation, post-process / data-flow type, began from mid of 80s, such as AVS, IRIS Explorer, IBM Visualization Data Explorer, etc. Now is the third generation, its key is to handle data, especially to handle 3D objects directly.

There are no clear boundaries among generations of this annalistic style

classification. And the relationship among generations is not that the newer one instead the older one as word "generation" means. We present taxonomy of visualization systems by feature of software which fits the concerns of both developers and users. There are four classes systems. (For space-saving, we do not list the reference of systems, same as for techniques in Section 3.)

1) Visualization toolkit. They provide function of graphic programming for developers. Developers call graphic functions provided by toolkit to set up application in code form. Toolkit with computer language (e.g. C++, Visual Basic, Delphi, …) can implement very implicit application. Visualization toolkits include graphic libraries (such as OpenGL, Tcl/tk, …) and components (such as TeeChart, OpenViz, and GIS components, e.g. MapObjects, MapX).

2) Single-technique system. They provide sole visualization technique for user. Or they focus just one technique and provide some necessary interactions for this technique. When a visualization technique was born, sometimes researchers built a single-technique system for it to show the usability of this technique. So the system often has same name with the technique. This is a reason why some researchers confused systems and techniques in classifying visualization. Single-technique system has always single function (query function, often), such as FilmFinder, WebBook & WebForager, WinViz, …

3) Multi-technique-integrated system. Every technique has its advantage and short scope. Even of some techniques aimed at same application goal, there might be very different effects for users because of users' knowledge, specialization, practical experience, etc. So single technique often hardly fulfill user's practice requirement. More visualization systems integrate multiple techniques and provide abundant display functions and interactivities. So they are more universal and more commercialized, e.g., Data Visualizer, VisDB, ADVISOR, DataDesk, also include many statistics and digital-sheet softwares. These systems provide functions as menus in system interface and users hardly extend functions. "Turnkey system", or "jailer system", is the pictorial name for them. Another problem of these systems is that users cannot effectively organize many techniques as a flow of process and analysis. So there is little collaboration among multiple techniques. The power of system is limited for complex scientific analysis.

4) Workspace. They provide extensibility for user to customize flow of visualization analysis. Current visualization workspace systems provide mainly extensibility with code-programming (such as using Macro language) and extended package for fields by producer. Examples are Xgobi, XmdvTool, IDL, Matlab, ArcInfo, MapInfo, … The requirement of programming ability for field users is the barrier. A solution is to provide visual programming and visual model-building environment. So specialists can focus on building model without thinking of details

programming and use basic components visualized to customize their analytic module. Recently, this type of workspace is advent, e.g. AVS, apE, Visualization Data Explorer, IBM OpenDX, VIP, ASVE, GeoVISTA Studio, etc. Their system structures are mainly based on data-flow model.

Among types of visualization systems, workspace systems, especially with visual programming, have advantage of extensibility, programming function, and availability. Although the research for them is still immature, we think it being an important developing direction.

5.   Summary and Discussion

The former sections present taxonomy for visualization techniques with two frameworks after reviewing current taxonomies. For clarifying the confusion of techniques and systems that some researchers deal improperly, we also present taxonomy for visualization systems. The key idea for both taxonomies is that concerns between users and developers of visualization techniques are different.

From our classification for visualization techniques and others taxonomies, we can find that most researches about visualization techniques focus on algorithm of visualization representation aiming to overview. The interactivity is more limited on directly handling views. As soon as view is displayed, later important analytic works, including hypothesis-making, pattern discovery, and result verification, are completely pass burden to users. These visualization techniques lack analytic function, such as to discover patterns hided beneath large dataset. Their functions stop at representation stage of visualization. Furthermore, their interaction level in analytic process is also limited for this.

The full composition of visualization includes representation and interaction. And the full meaning of visualization should be analysis rather than representation. So visualization techniques should join into the whole process of users' analysis and help users to "drill-down" and make visual thinking by combination of computer's power of computation and human ability of visual analysis.

Geo-visualization integrates approaches from visualization in scientific (ViSC), cartography, image analysis, information visualization, statistics, exploratory data analysis (EDA), spatial data mining and GIS to provide theory, methods, and tools for visual exploration, analysis, synthesis, and presentation of geospatial data (MacEachren and Kraak, 2001). So many involved disciplines and features originally from geo-domain make the techniques of geovisualization being difficult to build. In 1995, the International Cartographic Association (ICA) formed a Commission on Visualization whose focus is on use of dynamic maps as prompts to thinking. One of aims is to facilitate connections among cartographic researchers around the world and researchers in other disciplines working on various aspects of scientific visualization (MacEachren and Kraak, 1997).

Our classification also shows that the research of geo-visualization

techniques and systems is stepping from visualization representation to powerful visualization analysis that a good example is GeoVISTA Studio (Gahegan et al., 2002). This is closer to the full meaning of visualization. And this development promises us a fine perspective of spatial analysis.

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